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RESEARCH PAPER

Investigation on the Electrical Resistivity of Biopolymer Treated Sand and its Influencing Factors

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Abstract

The primary objective of this study was to examine the electrical resistivity of the biopolymer-treated sand (Agar and casein) and relate it to the unconfined compressive strength (UCS). The controllable factors used in this study are the degree of compaction or relative density, the kind and content of the biopolymer, dehydration duration, water content, and porosity. Utilizing scanning electronic microscopic techniques, mercury intrusion porosity, and connections with electrical resistivity, the dispersion and the structure of biopolymer inside the sand were examined. The outcomes demonstrated that electrical resistance decreases as biopolymer content and dehydration duration rise. The electrical resistance rises as the porosity and initial water content decrease. An empirical formula for electrical resistance was proposed, combining the effects of porosity, biopolymer content, and dehydration time. The electrical resistivity of sand treated with casein was shown to be correlated linearly with UCS, but the electrical resistivity of sand treated with Agar was found to be correlated second-degree polynomially with UCS. In order to predict electrical resistivity and identify the factors that have an excessively great impact on the electrical resistivity of soil treated with biopolymers, artificial neural networks were lastly built.

Keywords Electrical resistivity · Biopolymer treated soil · Casein and agar · Unconfined compressive strength · Artificial neural network

1 Introduction

The pursuit of environmentally sustainable practices and zero environmental effects from engineering practices underscores the need of advancing existing techniques and materials while exploring novel avenues (Chang et al.2016; Chang et al. 2020). Therefore, in an effort to reduce the effects on the environment, biological procedures have lately been created. Among other biological techniques, biopolymers are environmentally friendly and do not harm the environment during the production phase or after usage, in contrast to traditional soil-improvement admixtures like cement and chemical grouts (Chang et al. 2019; Shariatmadari et al. 2021; Fatehi et al. 2021). Biopolymers are polymers made by living organisms that fill in the voids of soil and improve it immediately without triggering the microbial process. The applications of granular sandy soils performance improvement using mixing biopolymers have been researched by many specialists (DeJong et al. 2006; Taytak et al. 2012; Khatami and O'Kelly 2013; Qureshi et al. 2017; Bonal et al. 2021). Xanthan, gellan, guar gum, alginate, and agar are examples of biopolymers that significantly enhance the mechanical characteristics of soil (Sujatha et al. 2021; Tran et al. 2022; Kumar et al. 2021). Additionally, casein was discovered to increase the sand's strength (Fatehi et al. 2018). Generally, in a variety of geotechnical applications, including subgrade improvement, soil strengthening, slope stability, surface erosion avoidance, and hydraulic barriers, researchers have used biopolymers. For instance, Chang et al. (2015) studied the effect of agar gum and gellan gum on two types of soil (sandy& clayey). They found that gellan gum has higher wet strength than agar gum for both soils. However, the dry strength of agar gum was higher than gellan gum for the sandy soil. Chang and Cho (2014) conducted additional laboratory testing on the geotechnical behavior of beta-glucan-treated soil. They observed that swelling behavior, Atterberg limits, and plasticity index are increased beside the incompatibility, while

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the coefficient of consolidation is decreased. Mahamaya et al. (2021) studied the interaction between three biopolymers (Xanthan gum, guar gum, and carboxymethyl cellulose) with two dispersive materials (fly ash and coal mine) by conducting water and wind erosion resistance tests. They concluded that 1% of biopolymer could mitigate the dispersiveness of these materials. Anandha Kumar and Sujatha (2021) have investigated the hydro-mechanical behavior of three biopolymers (Xanthan gum, guar gum, and β-glucan) amended sand-clay mixture for landfill. Their investigations showed that all the selected polysaccharides improve the heavy metal adsorption capacity of the sand-clay mixtures by reducing permeability. Lee et al. (2019)have used the soil stabilization technique for road construction (shoulder and subbase) for economic purposes. They used xanthan gum as an alternative eco-friendly material and compared it with the geomaterial in environmental, economic, and engineering performance. The xanthan gum has higher strength and ductility compared with geomaterial, which shows promising potential as an alternative material for road construction.

As shown above, multiple applications for biopolymer-treated soil have been explored in the literature. However, the mechanisms of the application of electrical resistivity to assess the engineering characteristics of biopolymer-treated soil are not clear. The electrical resistivity is widely used as a non-destructive test to assess soil performance. Over the past few decades, numerous studies have explored electrical resistivity and its connection with the mechanical and geotechnical properties of various soil types (Cao et al. 2018; Oloruntola et al. 2022). Ogungbe Abiola et al. (2021) conducted geophysical examinations of road collapse using two-dimensional (2D) electrical resistivity imaging and concluded that the wet sands and clay topsoil/subgrade soils were the main causes of road pavement collapse. Liu et al. (2020) investigated multi-scale examinations, including electrical resistivity, on soil treated with sulfur-free lignin polymer (SFL), a byproduct of the bioethanol industry. As the SFL content increases, the electrical resistivity of soil stabilized with SFL decreases. This is mostly because SFL powders are combined with soluble salts during the pre-treatment phase of the bioethanol production process, which raises the solute ion concentration in the pore fluid. An examination of the electrical resistivity of silt treated with lignin biopolymer was conducted by Cai et al. (2016); they found that the curing period had a significant effect and that the electrical resistivity of the treated soil decreased with additive quantity.

The main goal of this study was to explore the electrical resistivity behavior of the biopolymer-treated soil and investigate its influencing factors. Herein, agar gum and casein mixed with sand have been used to investigate the electrical resistivity. Porosity, water content, biopolymer type, and content, degree of compaction or relative density (molding points), and dehydration time were all taken into consideration as factors that could affect the electrical resistivity of the sand treated with agar gum and casein. Based on an unconfined compressive test, the relationship of the strength of the biopolymer-treated sand with the electrical resistivity is found. The artificial neural network method is developed to determine how the influencing factors effect on electrical resistivity of biopolymer-treated soil.

2 Materials and Methods

2.1 Materials

2.1.1 Sand

In this work, a standard Harbin sand, known as poorly graded Sand with the main properties listed in Table 1 is used.

2.1.2 Biopolymers

2.1.2.1 Casein Commercial casein biopolymer with a molecular weight of 20–25 kDa and the chemical formula of $C_{81}H_{125}N_{22}O_{39}P$ has been used. In a suspension phase, casein has a tendency to coagulate and form colloidal micelles with a radius between 50 and 500 nm and a molecular weight between 103 and 39,106 kDa (Dalgleish 1998; Fox et al. 2015). Thousands of casein molecules are used to create 94% of the micelles, which are held together by hydrophobic interactions and calcium ions. Moreover, 6% of casein molecules are composed of amorphous calcium phosphate, whereas protein molecules contain phosphoryl residues. Several variables, including the casein concentration, salt concentrations, pH level, and temperature, have an impact on the casein solutions (Chang et al. 2018; Fatehi et al. 2018). Also, it was discovered that the casein sample and the alkali used to dissolve the casein into the solution affected the minimal apparent viscosity of the casein solution (Dolby 1961). A reasonably well-established correlation between temperature and viscosity also indicates that casein is stable in high-temperature conditions. In this study,

Table 1 Physical properties of soils

Soil type	D50 (mm)	Cu	Cc	e_{min}	e_{max}	Gs	$\gamma_{dry\ max}$	OMC (%)	UCS KPa
sand	0.56	3.73	0.71	0.614	0.998	2.75	1.703	14.33	21.88

casein was made soluble in water using powdered calcium hydroxide.

2.1.2.2 Agar gum Commercial Agar biopolymer is used with agarose as the main component and the gelling agent. Alternating units of (1–4)-linked 3,6- anhydro-a-Lgalactose and galactose molecules based on a disaccharide repeat structure of 3-linked -D-galactopyranosyl make up its structural unit(Duckworth and Yaphe 1971). The capacity of Agar to generate reversible gels by chilling hot water solutions without additional chemical treatment is its most significant characteristic (Imeson 2009). Agar has a melting point of 85–95 °C and a gelling point of 32–45 °C. At 20 °C, 1.5% agar gel strength ranges from 70 to 1000 g/cm3. At 60 °C, 1.5% agar has an average molecular weight of 36–144 kDa and a viscosity of 10–100 centipoise (Rhein-Knudsen et al. 2015). Agar gelation is formed by settling water molecules into the spaces between the Agar double helices, contributing to the stability of the double helix formed by agar molecules into double helices with a threefold screw axis (Arnott et al. 1974). According to SEM pictures, the agar powder's particles are primarily flaky in shape. Additionally, microbial growth has no impact on the gel because Agar is not enzymatically degradable by the majority of bacterial species. As a result, it doesn't degrade much due to microbial activity.

2.2 Methods

2.2.1 Casein Solution Preparations

An appropriate alkaline ($Ca(OH)_2$) solution is made to dissolve casein uniformly for effective sand-casein mixing. To ensure complete dissociation of casein micelles, $Ca(OH)_2$ is added to water in a mass ratio of $Ca(OH)_2$ to casein = 14 to 100. The dissolvability of casein is increased by raising the $Ca(OH)_2$ solvent's temperature to 70°C. Using a magnetic stirrer, casein is added to the solvent and swirled continuously until all casein solids (powder) are completely dissolved, and a homogeneous casein solution forms under isothermal conditions (70°C). The same process is used to make all casein solutions. Casein solutions are prepared according to the target concentration (2%, 3%, and 4%, relative to the mass of the soil) of the casein–sand mixtures, in order to investigate the effect of casein concentration on the electrical resistivity of sand treated with biopolymers. The specimens with a minimum of 2% casein-to-sand ratio were selected to guarantee that they did not distort throughout the extrusion process from the mold. We have then raised the casein by 1% intervals up to 4% in order to investigate the impact of casein content on the electrical resistivity. To boost the workability and create a stiff casein-soil structure, 2%, and 3% casein-to-soil ratios were added while maintaining the soil's original ideal moisture content at 14%. At moisture concentrations of 18% water to sand ratio, a 4% casein to sand ratio was applied.

2.2.2 Agar Biopolymer Solution

For similar reasons to casein, agar content was chosen, but because it does not distort when extruded from the mold, a minimum agar to sand ratio of 1% was chosen. The agar biopolymer powder was weighed using the matching agar-to-sand ratios of 1%, 2%, and 3% in order to examine the impact of agar concentration on electrical resistivity. The matching 25% water to soil mixture was heated to 85 °C before the Agar was added. The mixture was constantly stirred until all of the agar particles (powder) were completely dissolved and an isothermal agar solution formed. Then we have mixed Agar solution with soil in the form of a hot solution and letting it gel within the pore spaces of the soil sample; this property of Agar was used to generate homogenous soil specimens.

2.2.3 Sample Preparations and Experimental Procedures

2.2.3.1 Relative Density and Porosity The different biopolymer-sand mixtures are prepared into 39.1 mm-diameter and 80 mm-high cylinder molds, which are compacted on four different relative densities of 35% (A4), 50% (A3), 65% (A2), and 85% (A1) of the original soil. This is done in order to investigate the electrical resistivity of biopolymer-treated soil. By altering the molding conditions, it was possible to adjust the void and porosity of compacted soils as well as their mechanical and resistivity characteristics. These compaction parameters were carefully adjusted to avoid exceeding the modified energy and optimal moisture content of all attempts while taking into account anticipated field conditions. For each sample, three tests were performed, and the average results for each treatment were recorded to guarantee that the findings were consistent throughout all investigations. Any departure from the median was regarded as smaller than 5%.

2.2.3.2 Dehydration Time (Dry Environment) When the soil stabilized with biopolymers undergo a period of dehydration, its water content is changed and the shrinkage of specimens is happened. As a result, the length of time the soil is dehydrated affects its strength and electrical resistance. Chang et al. (2015) showed that moisture content, not curing time, determines the agar biopolymer's strength.

Casein dehydrates more quickly than other biopolymers, and it takes seven days for it to attain its maximum compressive strength (80%), according to Fatehi et al. (2018). Since the water content is a key element affecting electrical resistivity, it is expected that when soil dehydrates, its resistivity will vary. Electrical resistivity was tested in our study at varied dehydration times of 5 days, 10 days, and 21 days. These dehydration periods were selected to represent various field circumstances at various moisture contents in dry environments. The materials that had been dehydrated for 21 days were then measured using the unconfined compressive test.

2.2.3.3 Initial Water Content (Wet Environment) To explore the electrical resistivity of biopolymer-treated soil under wet conditions, we have adjusted the initial water content of the samples and the samples were immediately tested for electrical resistivity. We first prepared the casein-treated sand specimens at the ideal moisture content of the original soil (14%), due to the decreased viscosity of the casein solution. Then, as the casein content rose, we found that the casein-treated sand's workability reduced. This led to a lot of voids on the casein-treated sand samples' surfaces, which may indicate inadequate mixing. As a result, we have chosen to gradually raise the initial moisture level by 2%. Therefore, the initial water contents of 14%, 16%, and 18% were chosen for every casein content. By adding more water to the sample mixing process, the casein-treated sand became more workable. To make sure that every sample could survive on its own without showing any noticeable deformation as it extruded from the mold, a maximum starting water content of 18% was chosen. Similar processes were carried out for sand that had been treated with agar; however, because agar has a higher viscosity than casein, a minimum initial water level of 25% was established in order to improve the workability and mixing process. Since the workability of agar-treated sand remains unchanged every 2% interval, we decided to raise the initial moisture content at intervals of 5% in order to ensure maximum workability and prevent numerous voids in the specimens. For every agar content, 25%, 30% and 35% initial water content were chosen. The samples were prepared into 39.1 mm-diameter and 80 mm-high cylinder mold in which its bottom and top attached with stainless electrodes to measure their electrical resistivity.

2.2.4 Test Methods

Volume and mass measurements were made prior to electrical resistivity measurements in order to determine the specimens' densities. Each specimen's electrical resistivity was assessed using the plate-and-two-electrode method using a EUCOL U2830 LCR meter. During the electrical resistivity test, two stainless electrodes with a 50 mm diameter and a thickness of 2 mm were positioned on the top and bottom of the specimens. To ensure a good contact between the specimen and the stainless electrode, a vertical pressure of 5 kPa was applied to the electrodes. The electrical resistivity and strength of the specimen were found to be barely impacted by this pressure. The frequency of 1 kHz was chosen to assess electrical resistance. Testing for electrical resistivity was done at a constant temperature of 20 °C.

Following the measurement of electrical resistivity, the unconfined compressive test was carried out on the specimens dried for 21 days in accordance with ASTM D2166/D2166M-16 at a strain rate of 1%/min. After the unconfined compressive test, the specimen's water content was also determined. Mercury intrusion porosity (MIP) was performed on biopolymer-treated sand at various types and concentrations of biopolymer for the specimens that compacted at a relative density of 85% in order to analyze the geometry and dispersion of the biopolymer in the granular medium and connect it with the results of electrical resistivity. Various bond topologies are anticipated with varying biopolymer contents, resulting in materials with various pore diameters and shapes. These characteristics are examined in this work because they significantly impact the electrical and mechanical characteristics of soils treated with biopolymers. In addition, An scanning electronic microscopic (SEM) image was acquired to capture the physical interaction between the sand and biopolymer at the microscopic level and confirm the geometry of the biopolymer in the granular medium. Disturbed samples are only evaluated by SEM at 4% of the calcium caseinate biopolymer-to-sand ratio and 3% Agar biopolymer-to-sand ratio.

3 Theory

3.1 Electrical Resistivity Theory

One of the nondestructive techniques that can be used in the field as well as in the lab is the electrical measuring technique, which is regarded as a nondestructive geophysical technique in the latter situation (Cardoso 2016). The primary parameters affecting soil resistivity include water content, porosity, density, degree of saturation, particle shape, orientation, and ion concentration of pore solution (Kibria and Hossain 2012; Ryu et al. 2014). Soil resistivity is an inherent feature of the material. The electrical resistivity approach has been utilized in earlier research to explore the engineering qualities of soils and rocks (Abedi-Koupai and

Mehdizadeh 2008; Oh et al. 2015), to track contaminants and map contaminant transit in soils (Damasceno and Fratta 2006), and to find flaws and heterogeneity in landfill cover material. Previous research has integrated the resistivity of solids, liquids, and air into a model of soil resistance using a parallel connection, a series connection, or a compound model of these two connections (Mitchell 1991). In order to link the electrical resistivity of saturated sand (ρ) to the electrical resistivity of pore fluid (ρf) and porosity(n), Archie (1942) created an empirical law. The fundamental Archie's law is as follows:

$$\rho = a.\rho_f.n^{-m} \quad (1)$$

where m is the cementation exponent, and a is the fitting parameter. The tortuosity and pore network interconnectivity greatly impact the value of m and m = 1, resulting in a complete pore fluid connection. According to Archie (2003), the value of m was tested as 1.3 for loose sand and varied from 1.8 to 2.0 for cemented sand. For saturated sand with a porosity of 0.3–0.49, Friedman and Seaton (1998) proposed a value of m = 1.38–2.3. According to a review of the literature by Friedman (2005), the value of m for saturated geomaterials ranged from 1.2 to 4.4 depending on the porosity, grain size distribution, particle shape, and consolidation condition. The degree of saturation in unsaturated soil is also correlated with soil resistivity. According to Frischknecht (1996), the following Equation connected the electrical resistivity of unsaturated soil (ρ) with the electrical resistivity of saturated soil (ρsat):

$$\frac{\rho}{\rho_{sat}} = S_r^{-b} \quad (2)$$

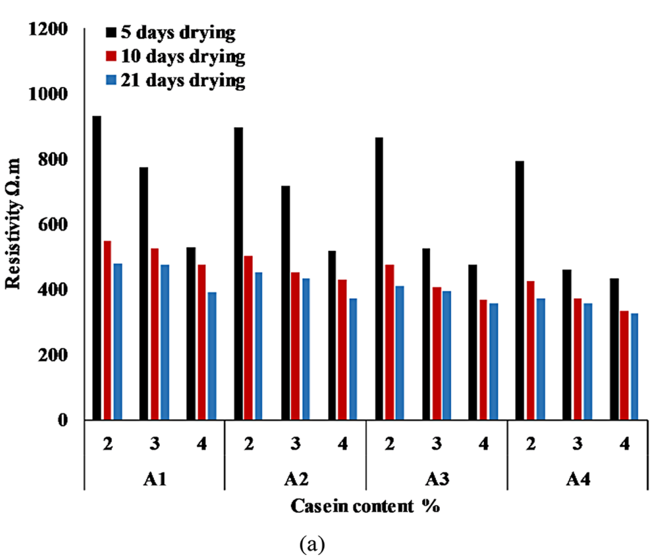
where b is the empirical factor, and Sr is the saturation level.

4 Results and Discussion

4.1 The Influence of Biopolymer Type and Content, Microscopic Interaction, Dehydration Time and Drying Mechanism on the Resistivity in Dry Environment

4.2 The Effect of Biopolymer Type and Content

In Fig. 1, the impact of casein and agar contents on electrical resistivity at various relative densities and dehydration times is depicted. When the biopolymer content increased, the electrical resistivity of the casein-adjusted sand was seen to decrease (see Table 2). For instance, when the casein content was increased from 2 to 4% during five days of dehydration, the electrical resistivity decreased from 930 Ω.m to 529.903 Ω.m. Two features of the casein content's impact on the resistivity of casein-treated soils can be found: first, when $Ca(OH)_2$ is added to casein, it is changed to anionic biopolymer(Fatehi et al. 2021); therefore, the addition of calcium caseinate causes an upward trend in the pore solution's ion concentration, and the presence of ions enhances the flow of electrical current. As a result, as the amount of casein in the solution increases, its electrical resistance decreases. In addition, the geometry and dispersion of the casein biopolymer in the soil, which will be clarified later in this study by the MIP test, can be used to infer the decrease in resistivity with increasing casein concentration. In line with this pattern, a rise in agar biopolymer causes a decrease in electrical resistance. For instance, the electrical resistivity



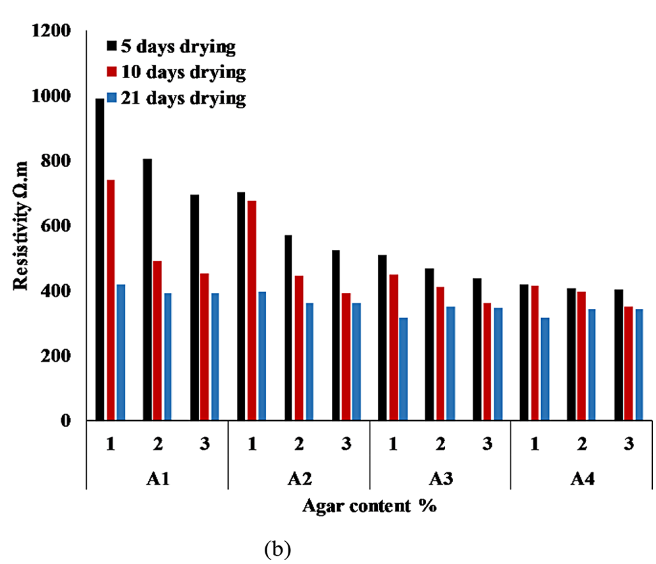


Fig. 1 The influence of biopolymer content and relative density on the electrical resistivity of **a**) casein-amended soil; **b**) agar-amended soil

Table 2 The influence of biopolymer content, dehydration time and relative density on the electrical resistivity of casein-amended soil and agar-amended soil

Casein biopolymer treated soil					Agar biopolymer treated soil			
Relative density (%)	Biopolymer content (%)	Resistivity (Ω.m)			Biopolymer content (%)	Resistivity (Ω.m)		
		5 days drying	10 days drying	21 days drying		5 days drying	10 days drying	21 days drying
85	2	930.000	549.209	481.246	1	989.910	739.988	418.507
	3	773.623	524.089	475.983	2	804.136	491.075	392.617
	4	529.909	475.990	390.765	3	693.555	453.161	391.022
65	2	897.537	501.242	452.356	1	701.697	675.093	394.015
	3	716.438	454.073	433.267	2	570.695	443.318	361.370
	4	518.521	429.385	372.450	3	525.438	393.453	361.172
50	2	868.147	475.569	409.886	1	509.144	446.796	316.053
	3	526.392	405.225	395.068	2	465.850	409.448	351.924
	4	476.158	368.149	357.482	3	435.892	363.358	345.023
35	2	794.167	425.725	370.804	1	418.258	413.522	314.962
	3	461.754	372.023	355.510	2	405.857	396.039	344.093
	4	434.039	334.080	327.191	3	403.841	351.924	343.428

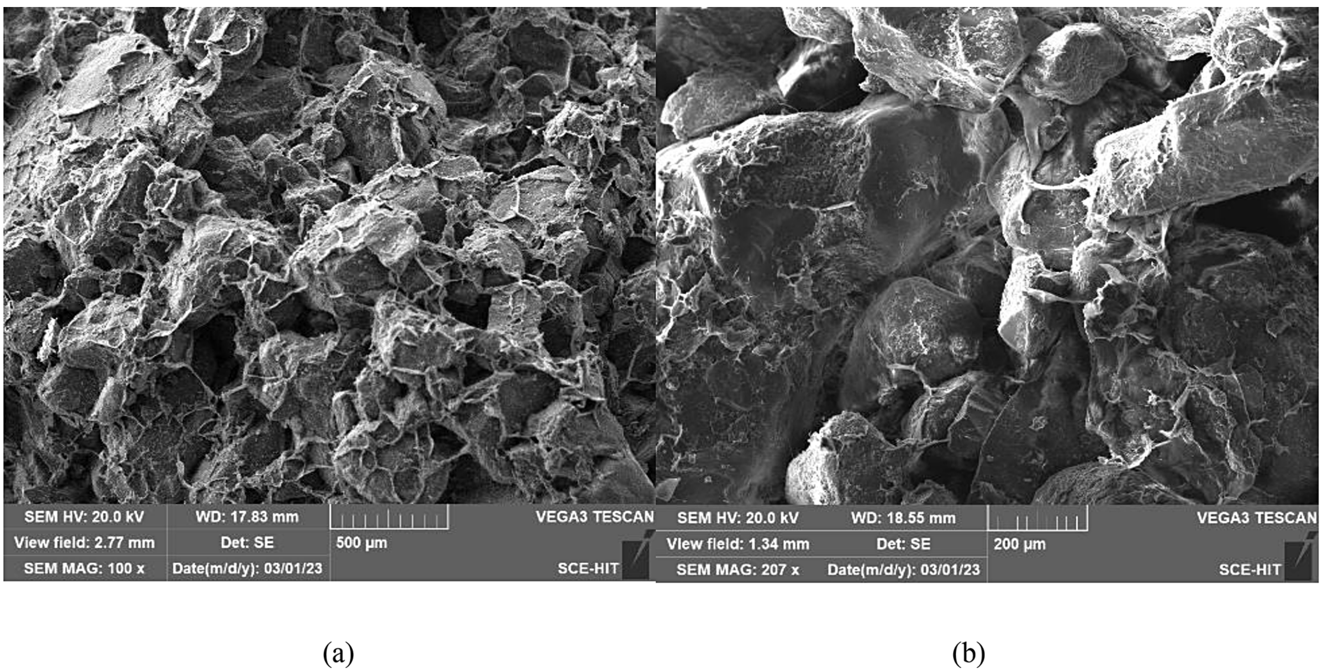


Fig. 2 SEM image of (**a**) 4% casein-treated sand; (**b**) 3% agar-treated sand

reduced from 989.910 Ω.m to 693.554 Ω.m when the agar content was increased from 1 to 3% during five days of dehydration. Increasing the agar concentration causes the maximum dry density to decrease, creating more voids in the specimens and lowering electrical resistance and increasing electrical conductivity.

4.2.1 The Effect of Microscopic Interaction and Dehydration Mechanisms on the Electrical Resistivity

4.2.1.1 SEM Image Figure 2 displays SEM pictures of the sand that was treated with biopolymer. Figure 2 shows that a thin layer of polymeric membranes was applied to the sand particles. The reason for this is the sol-gel property, which allows the polymer solution to be widely and evenly dispersed among the sand particles and to stick to their surface prior to gelation. In order to achieve soil fortification, biopolymer matrix depends more on physical interactions. It can fill in gaps and take the shape of threads or membranes to establish direct connections between two distant particles. Consequently, particle bridging, pore filling, and surface enwrapping can be generally linked to the stabilizing process of biopolymer treatment. The biopolymer matrix contracts as a result of dehydration, increasing inter-particle

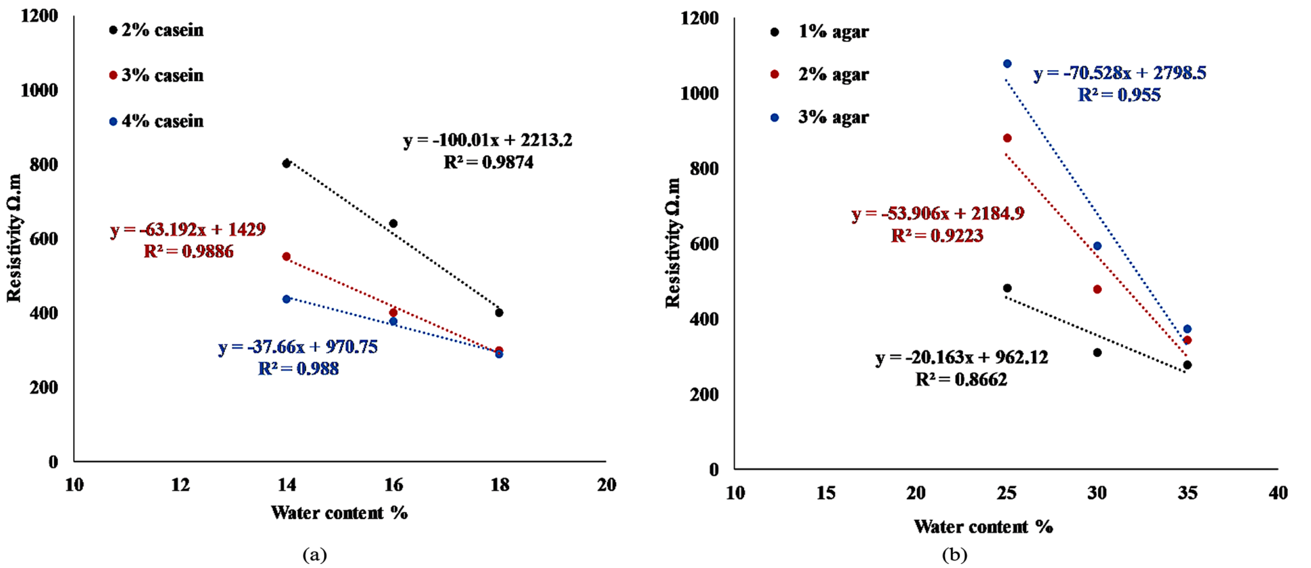


Fig. 3 The relationship between the electrical resistivity and water content for **a**) casein treated soil;**b**) agar treated sand

tensions. The dense inter-particle arrangement and strong cohesion are produced by the three-dimensional network structure made up of several small threads and membranes. Therefore, the presence of this inter-particle structure yields good benefits in understanding the underlying mechanisms of electrical resistivity, even if the natural sand was treated with a minor amount of polymers. Stronger inter-particle bonding result from the polymer's ability to better fill gaps and collect on the particle surface at higher concentrations.

4.2.1.2 The Effect of Dehydration time on the Electrical Resistivity The electrical resistivity of sand treated with biopolymers reduced as the dehydration time increased, regardless of the biopolymer type, content, or degree of compaction. For instance, at 2% casein concentrations compacted at 85% relative density, the electrical resistivity decreased from 930 Ω.m at five days of drying time to 481.246 Ω.m at 21 days of drying time, while at 3% and 4% casein concentrations, it decreased from 773.623 Ω.m and 529.909 Ω.m at five days of drying time to 475.983 Ω.m and 390.765 Ω.m, respectively, at 21 days of drying time. Actually, as the casein-treated sand is drying, the electrical resistivity is decreased. The decrease in electrical resistivity with dehydration time is caused by the casein turning from solution to gel in the sand pores and a decrease in the connectivity of the pore solution. Due to the volumetric shrinkage (gel contracts) brought on by the water loss, the biopolymer starts to gather together in a chain-like alignment when the hydrogel is dehydrated. Gel networking develops when the biopolymer gels almost completely dry and lose moisture, causing the biopolymer gel to compress more firmly. Then the gaps left in the biopolymer-soil matrix will widen. These three-dimensional gel network gaps within the sand pores, which are visible in the SEM picture in Fig. 2a, will improve electrical current flow and lower electrical resistivity.

The electrical resistance of agar-treated sand will also decrease with longer dehydration times. The electrical resistivity, for instance, decreased at 1% agar concentrations compacted at 85% relative density from 989.910 Ω.m at five days drying time to 418.507 Ω.m at 21 days drying time, while 2% and 3% agar concentrations decreased from 804.136 Ω.m and 693.555 Ω.m at five days drying time to 392.617Ω.m and 391.022 Ω.m, respectively, at 21 days drying time. The drying of water molecules that collect in the spaces between the double helices will leave the largest cavities through the sand pores, decreasing the connection of agar hydrogel in the pores and increasing the flow of electrical current in the soil and lower the electrical resistivity. This is how the effect of dehydration time on the resistivity of agar-stabilized soils can be explained. Hence, the main cause of the reduction in electrical resistivity, as revealed in the SEM image, is the decrease in connection of the pore solution caused by drying and creating three-dimensional gel networking (Fig. 2b). According to SEM image, the agar encased the soil grains in a three-dimensional gel network. It is also possible to see a few biopolymer connecting bridges that developed between the sand particles that were not in direct contact, which increase the current flow and reduce the electrical resistivity.

The electrical resistivity values of different biopolymer contents at longer dehydration times varied less than those obtained at shorter dehydration times, as can be seen. For instance, at the shorter dehydration time (5 days), the difference in electrical resistivity of 2% and 4% casein

concentrations is 400.090Ω.m, while at the longer dehydration time (21 days), the difference was 90.48Ω.m. Similar to this, at the shorter dehydration period (5 days), the difference between electrical resistivity of 1% agar concentrations and 3% agar concentrations is 296.355Ω.m, whereas at the longer dehydration time (21 days), the difference was 27.484Ω.m. At the longer dehydration time because the specimens were fully dried, a denser soil structure developed due to the volumetric shrinkage, which occurs during the air drying process in the soils treated with biopolymer and plays a major role in changing the electrical resistivity rather than the hydrogel. The difference in gel thickness at 21 days of drying in the sand pores at different biopolymer content will be less than that of hydrogel-gel thickness at five days of drying. Hence, for a longer dehydration time, the biopolymer content will have less impact on electrical resistance.

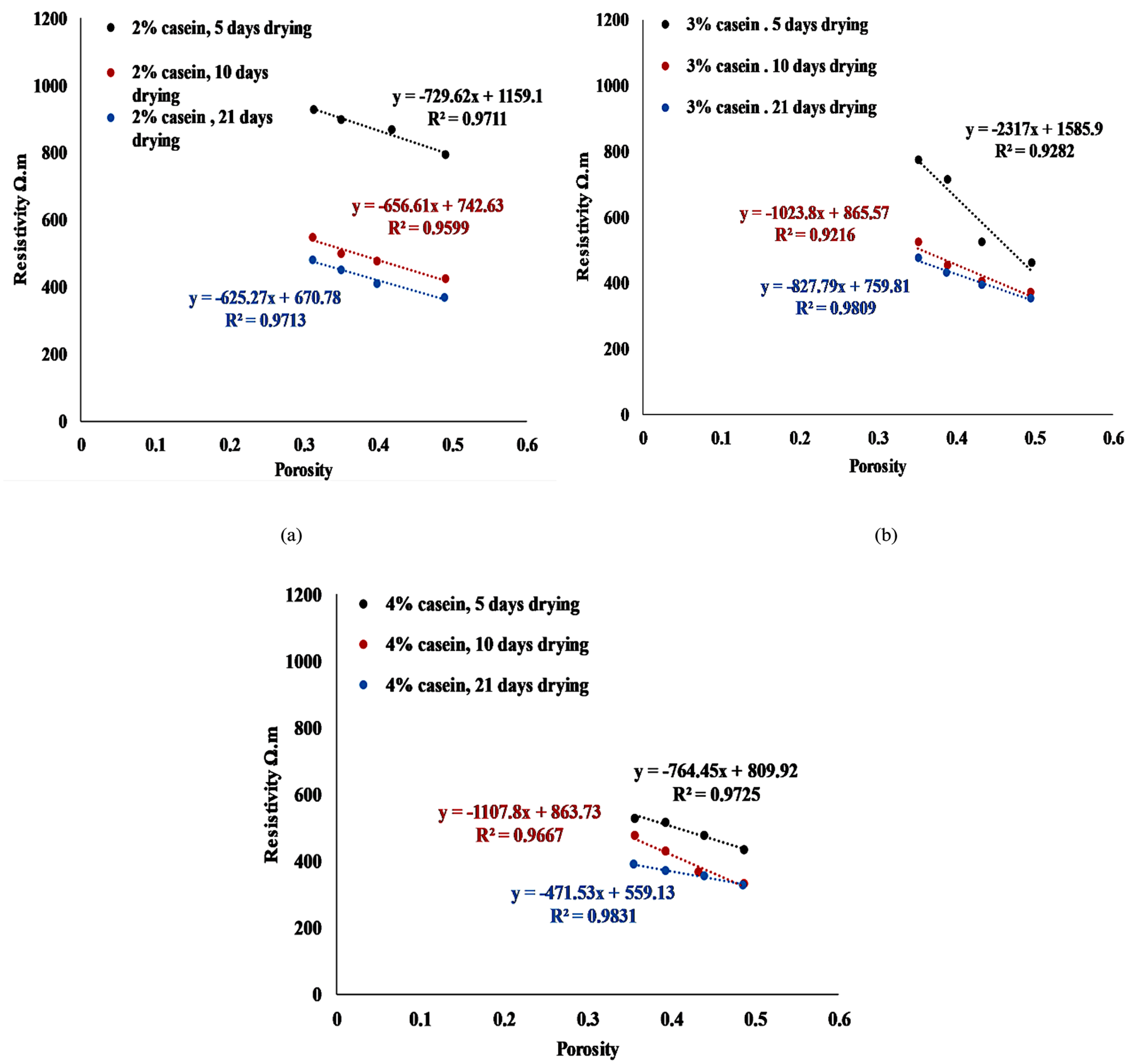
4.3 The Influence of Initial Water Content, Biopolymer Type and Content in Wet Conditions

For a proper knowledge and management of soil and water natural resources, soil water is essential. The timing of motorized operations in crop fields is determined by managing the water content of the soil. This also helps to define the ideal period for machinery traffic, avoiding excessively wet conditions, and preventing soil compaction (Sakai et al. 2015; Peixoto et al. 2019). The oven drying method is the conventional way to find the soil water. It is challenging to evaluate soil water using the conventional method, particularly for vast regions and even more so at varying soil depths. Furthermore, new methods must be used to monitor soil water in space and time with minimal disturbance to the soil and high accuracy because the conventional method is costly, labor-intensive, damaging, and time-consuming (Brillante et al. 2015). As a result, in recent years, indirect measurement techniques—which are mostly based on the electrical properties of soil—have become more popular. The water content has been estimated in the literature using the electrical resistivity of the soil. As a result, we have established in our study the trend between the electrical resistivity in wet conditions and the biopolymer content, as well as the link between the electrical resistivity of the biopolymer-treated soil and water content at different biopolymer contents.

The main results showed that as the biopolymer content increases in a wet environment(Fig. 3), the electrical resistivity decreases, exhibiting behavior comparable to that of a dry situation. Electrical resistivity dropped from 800.072 Ω.m to 438.72 Ω.m as the casein concentration grew from 2 to 4%, and from 1079.52 Ω.m to 480.92 Ω.m as the agar content climbed from 1 to 3%. The resistivity reduced under wet conditions as the biopolymer concentration increased, for reasons similar to those discussed in the preceding section (dry conditions). The water content of soil treated with biopolymer has a negative correlation with electrical resistivity, consistent with natural soil water. The precise correlations between soil moisture treated with biopolymer and electrical resistivity data acquired through experimental work are ascertained through the use of empirical linear regression. The electrical resistivity of 2% casein-treated sand dropped from 800.072 Ω.m to 400.036 Ω.m as the water content rose from 14 to 18%. As seen in Fig. 3, this behavior was demonstrated for every type and content of biopolymer utilized in this investigation. Our research aligns with previous studies conducted in the literature, indicating a non-linear and inverse relationship between soil water and electrical resistivity; that is, a greater electrical resistivity corresponds to a lower water content (Celano et al. 2011; Alamry et al. 2017).

4.4 The Influence of Porosity (Degree of Compaction) on the Electrical Resistivity of Biopolymer-Treated Soil

According to Archie (1942), soil porosity is a major factor in electrical resistivity. In addition, many studies have discussed the relationship between soil porosity and electrical resistivity. Oh et al. (2014) used experimental methods to investigate the connection between pore fluid porosity and the electrical resistivity of sand and clay. Their findings show that the sand samples have a typical Archie's law curve. Cardoso (2016) investigated the effects of porosity and tortuosity on the geophysical properties of artificially cemented sand. Li (2012) found that the electrical resistivity of the saline soil increased with increasing porosity and reduced with increasing water volume, salt content, and degree of saturation. The connection between the porosity and electrical resistivity of casein-added sand is depicted in Fig. 4. When casein content is known, a decrease in porosity or an increase in compacted relative density is seen along with an increase in electrical resistance. When the porosity rose from 0.31 to 0.49 (relative density decreased from 85 to 35%), the electrical resistivity decreased from 930Ω.m to 794.167Ω.m at 2% casein to sand ratio dehydrated for 5 days. Similar behavior was observed for casein to sand ratios of 3% and 4%. It should be noted that electrical resistance increases linearly as porosity decreases for various casein contents and dehydration times. The density of the casein gel networking that covers the sand will not effectively fill the pores when the void ratio is larger; as a result, the electrical current flow will increase, and the electrical resistance will decrease. In contrast, when the void ratio is smaller, there will be less space between the sand particles.



(c)

Fig. 4 The influence of porosity on the electrical resistivity of **a**) 2% casein to sand ratio; **b**) 3% casein to sand ratio; **c**) 4% casein to sand ratio at different dehydration times

As a result, the density of casein gel that fills the pores will be greater, reducing the electrical current flow and increasing electrical resistivity.

The link between agar-amended sand's electrical resistivity and porosity is depicted in Fig. 5. When the agar content is known, a decrease in porosity or an increase in compacted relative density is seen along with an increase in electrical resistivity. The electrical resistivity decreased from 989.910 Ω.m to 418.258 Ω.m at 1% agar to sand ratio dehydrated for five days while the porosity rose from 0.37 to 0.517 (relative density decreased from 85 to 35%). The same behavior was seen for Agar-sand ratios of 2% and 3%. It should be noted that adopting a second-degree polynomial connection was preferable to the R^2 of the linear relationship between the electrical resistivity of Agar treated soil and porosity. As a result, the electrical resistance of soil treated with Agar will decrease twice as porosity rises. When the void ratios and pore volume grow at a specific ratio of agar content, the cementations and filling behavior of agar gel will not be as effective as in the lower void ratio. As a result, the electrical

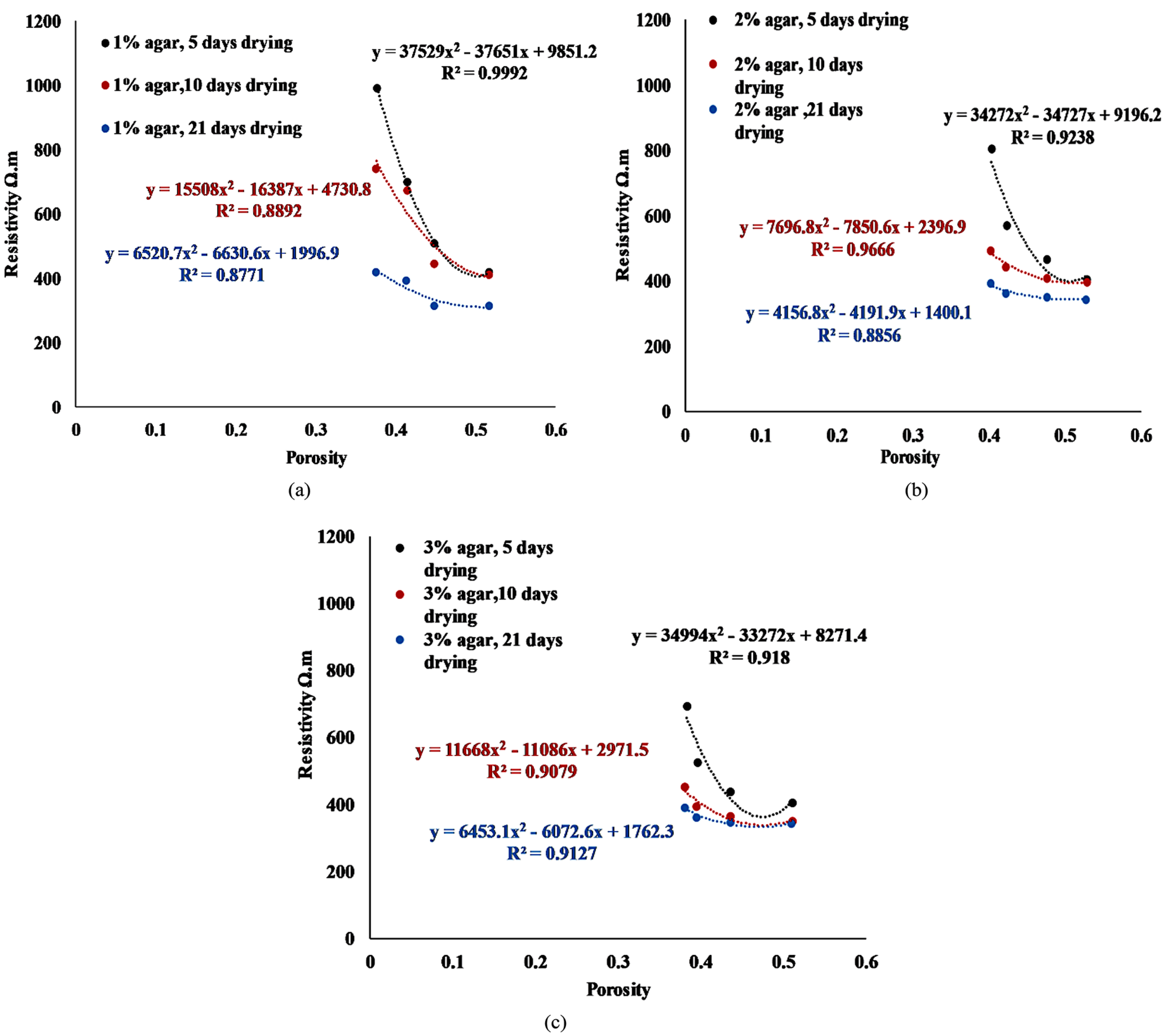


Fig. 5 The influence of porosity on the electrical resistivity of **a**) 1% agar to sand ratio; **b**) 2% agar to sand ratio; **c**) 3% agar to sand ratio at different dehydration time

current flow will be improved, and electrical resistance will be reduced due to the greater void ratio.

Similar trends to Archie's law can be seen in the test findings from samples of Agar and casein-modified sand. Hence, the application of Archie's law to the biopolymer-treated sand is possible. Unfortunately, the dry process of the biopolymer-treated sand and transitioning the biopolymer from solution status to gel status are not taken into account by Archie's law. As indicated in the next section, we looked into the link between porosity/ (dehydration time *biopolymer content) and electrical resistivity to consider the dehydration time of sand treated with biopolymer.

4.5 The Effect of Synthetic Parameter of (Porosity/ (Biopolymer Content*Dehydration Time)) on Biopolymer Cemented Sand

As was discussed in the previous sections, the electrical resistivity of biopolymer-treated sand is affected by both the biopolymer content and the dehydration period, in addition to porosity. Using a synthetic parameter that combines the effects of various variables makes sense. The electrical resistivity of biopolymer-treated sand has been correlated with the (porosity/ (biopolymer content*dehydration time)). There is no strong link between this ratio and electrical resistivity for samples of casein- and agar-treated sand, where the obtained R^2 was equal to 0.587 for casein- and 0.22 for

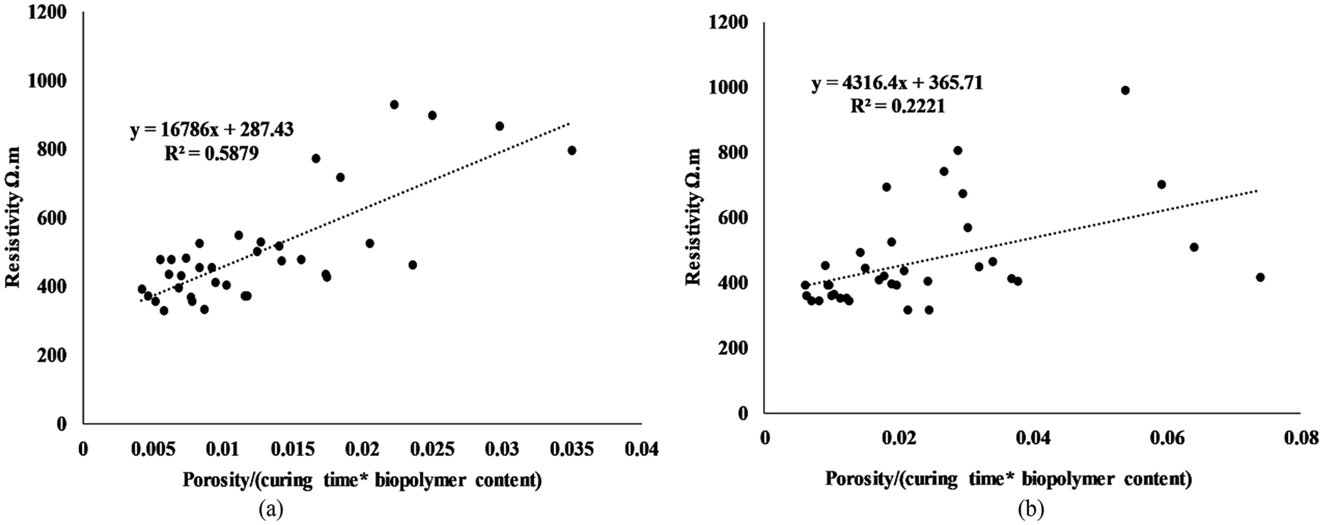


Fig. 6 Relationship between electrical resistivity and η/(b*t): (**a**) casein treated sand; (**b**) agar treated sand

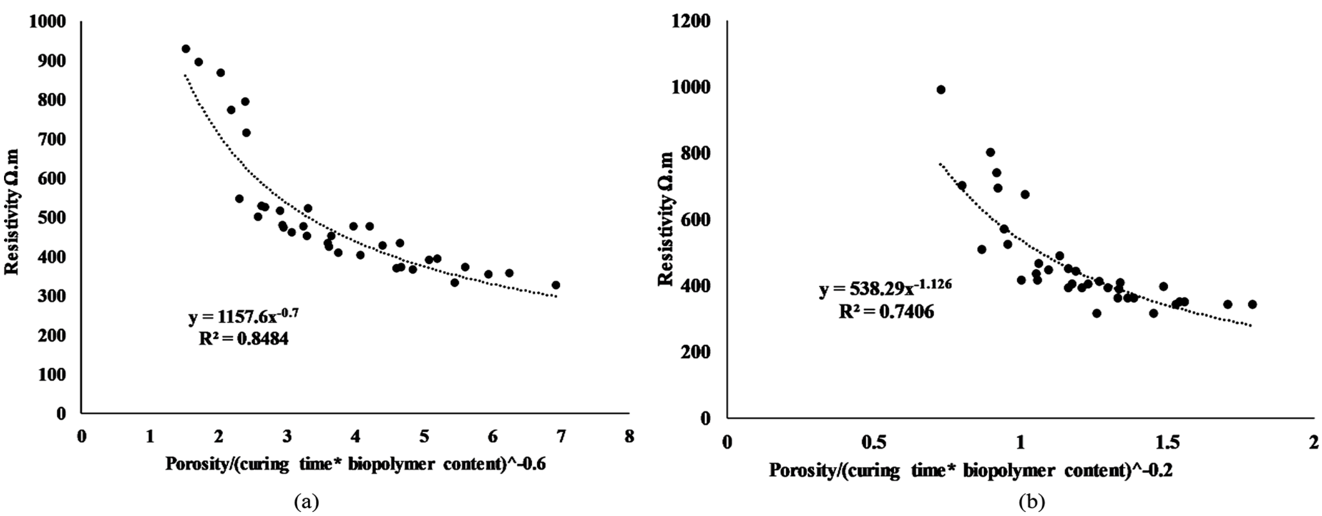


Fig. 7 Relationship between electrical resistivity and $\eta/(b^*t)^{-c}$: **a**) casein treated sand; **b**) agar treated sand

agar-treated sand (Fig. 6(a) and (b)). A second exponent (c), which similarly depends on the mathematical modification of the experimental data, is used to optimize the association between this ratio and the electrical resistivity of the biopolymer-treated sand. Hence, the resistivity (ρ) can be accounted for in the Eq. 3.

$$\rho = \frac{porosity}{(biopolymer\ content * dehydration\ time\ ratio)^{-c}} \tag{3}$$

The exponent c is dependent on the type of biopolymer, as seen in Fig. 7. In the current study, the casein-treated sand's c value is 0.6 and the agar-treated sand's c value is 0.2. It is clear that using an exponent c improves the control of the findings' adjustment curve. A power relationship between Eq. 3 and electrical resistivity of specimens, independent of the type of biopolymer, can be demonstrated by regression analysis, as shown in Fig. 7a and b. For instance, a power relationship was derived for casein treated sand and agar treated sand as shown in Eqs. 4 and 5, respectively.

$$\rho = 1157.6 * \left(\frac{\eta}{(b*t)-0.6}\right)^{-0.7} \quad \mathrm{R}^2 = 0.8484 \tag{4}$$

$$\rho = 538.29 * \left(\frac{\eta}{(b*t)-0.2}\right)^{-1.126} \quad \mathrm{R}^2 = 0.7406 \tag{5}$$

Where η is the porosity, b is the biopolymer content, and t is the dehydration duration.

Based on the above results, Eq. 6 can be used broadly to integrate the effects of porosity, dehydration duration, and biopolymer content. This confirms that it is possible to apply the Archie law to biopolymer-treated sand using these

linkages. The resistivity empirical formula of biopolymer-treated sand can be expressed as follow:

$$\rho = A\left(\frac{\eta}{(b * t)^{-c}}\right)^{B} \tag{6}$$

Where A, B, and c are fitting values that are calculated from experimental data, η is the porosity, b is the biopolymer content, and t is the dehydration duration. The biopolymer type being utilized to treat the sand will determine the parameters of A, B, and c. It should be emphasized that this Equation, derived empirically from experimental data, can only be used for sandy soil treated with biopolymer. More research must be conducted on various biopolymer-treated soil types. Notably, the resistivity formula suggested in this work is close to Archie's rule when Eqs. (1) and (6) are compared. Beside the linear relationship between water content of biopolymer treated sand and electrical resistivity, Eq. (6) can be used to expand Archie's law to apply to biopolymer-treated sand. It should be noted that Eq. (6) is an empirical resistivity calculation and has no particular physical significance. For engineering applications, the strong correlation between electrical resistivity and the ratio in Eq. (3) is sufficient.

The outcome demonstrates that electrical resistivity can be well adapted by a special power function with the ratio of Eq. (3). As a result, Eq. (6) can be utilized as a fundamental measure that is sufficient to describe the electrical resistivity of sand that has been treated with a biopolymer. Equation (6) beside the effect of water content can also be used to check and manage the subgrade and subbase condition of a pavement made of biopolymer-treated sand.

4.6 Resistivity and Pore Size Distribution of Biopolymer Cemented Sand

MIP test of soil has received a significant deal in the literature. Delage et al. (2006) examined the pore-size distributions (PSDs) of compacted bentonite and found that the radii of the intra- aggregate and inter-aggregate pores were around 0.02 and 0.2 µm. According to Li and Zhang (2009), a compacted geomaterial made of fully decomposed granite soil in Hong Kong has a threshold radius between intra-aggregate and inter-aggregate pores of 2 µm. The threshold radii between intra-aggregate and inter-aggregate pores and between inter-aggregate and air pores were reported by Horpibulsuk et al. (2009) to be 0.01 µm and 10 µm, respectively. Particle size distribution can be classified as either unimodal or bimodal, and they are two different varieties. Compacted soils, structured soils, and residual soils are all characterized by bimodal PSDs. Bimodal PSDs can also be seen in some pore media, such as broken rocks. Other compacted clay, sand, and lime-treated silt also exhibit the specimens' bimodal feature (Simms and Yanful 2001; Lee and Shang 2014). Meanwhile, coarse granular geomaterials usually exhibit unimodal PSDs(Zhang and Li 2010). The MIP test was carried out to comprehend the geometry and dispersion of the biopolymer in the sand and connect it with the electrical resistivity. After 21 days of curing, the particle size distribution curves of sand treated with various amounts of Agar and casein are examined in this study.

4.6.1 Casein Treated Sand

Two different types of pores are present, according to the combined data of the MIP tests. The pores with diameters more than 1000 nm are referred to as macropores and are the first. These are comparable to the substantial voids between sand grains where the conglomeration effect of casein is not present. The second type is the micropores, which primarily correspond to the spaces between casein gel networks that cover the sand particles and fill their pores. In Fig. 8a, treated sand with various casein levels is shown against the cumulative pore volume (V) of the unit weight sample and the pore diameter (d). All curves can be seen to have well-graded, smooth bounds, which suggests that pore sizes are within the range that may be detected. Sand treated with varying amounts of casein has a similar curve for total mercury intrusion volume. As can be observed, stabilized sand treated with 2% casein has the highest total mercury intrusion (0.207153 ml/g), followed by sand treated with 4% casein (0.19665 ml/g), and sand treated with 3% casein (0.169707 ml/g total mercury intrusion). The differential pore volume distribution curves of the specimens with various casein concentrations are shown in Fig. 8b. The figure clearly shows that pore size increases with increasing casein concentration. For instance, 4% casein-treated sand displays multi-peak pore size geometry, with the maximum peak intensity occurring at a pore size diameter of 145623.65 nm. Similar geometric behavior was observed for 3% casein-treated sand, with a slight shift to the left (corresponding to a slight reduction in pore size) and a decrease in peak intensity, where the greatest peak was located at 145544.9125 nm. Sand treated with 2% casein displayed altered geometry with just two peaks (bimodal structure), the greatest peak being at 121270.7125 nm (indicating a reduction of pore size). The electrical resistivity of casein-treated sand is consistent with this type of pore shape behavior of varied casein-content-treated sand. When the casein concentration was increased from 2 to 3 to 4%, the electrical resistivity of casein-treated sand that had been dried for 21 days dropped from 481.246 Ω.m to 475.98 Ω.m to 390.765 Ω.m. Hence, the mechanism can be described as follows: as seen in the particle size distribution curve, pore size increases as casein content increases. This increase in

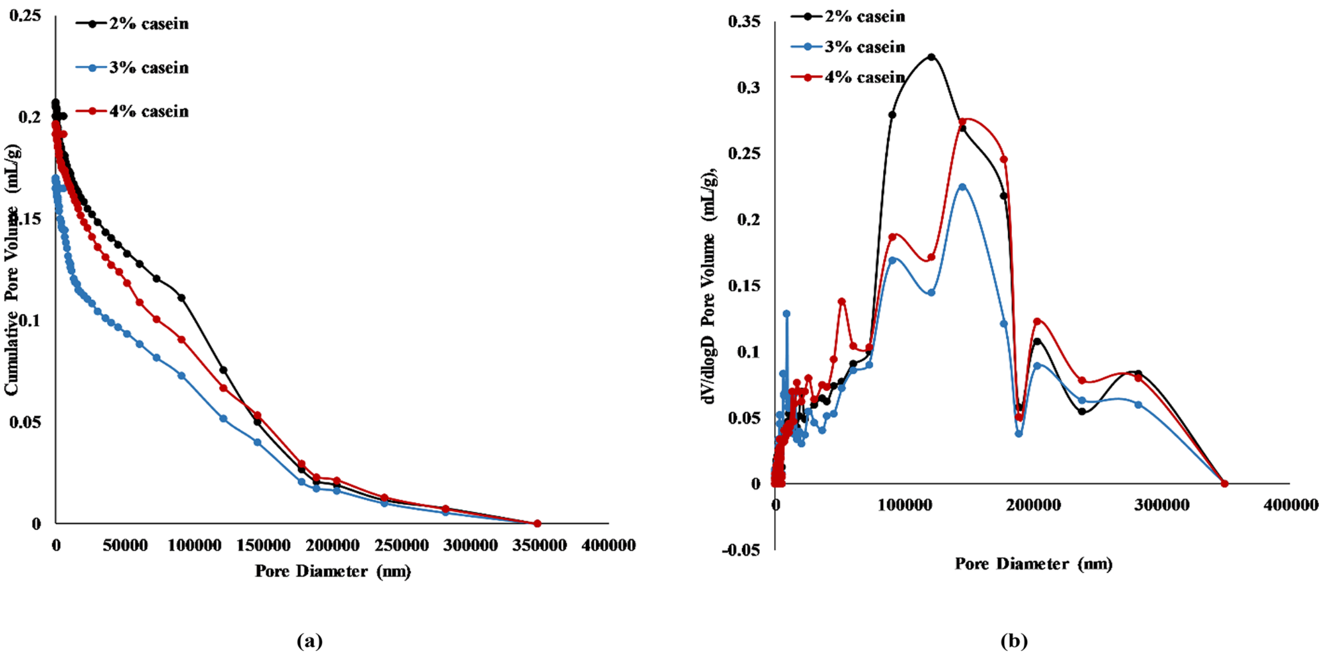
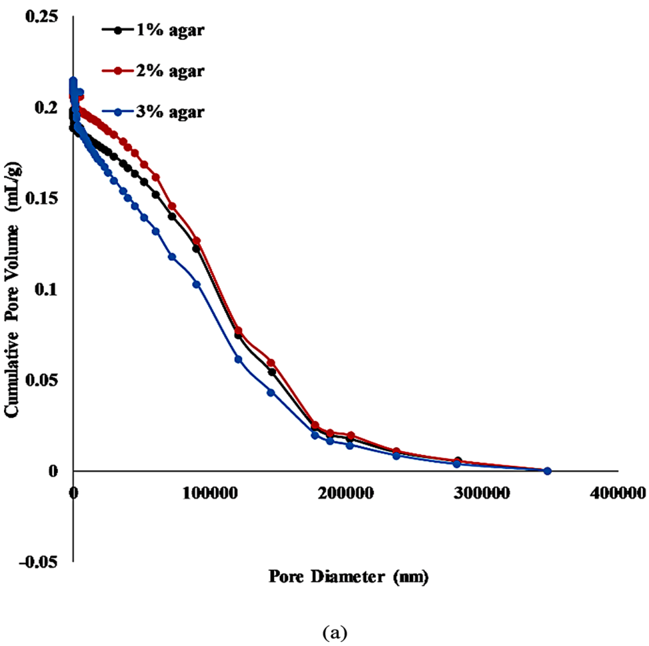


Fig. 8 Mercury intrusion porosimetry results of different casein content treated sand: (**a**) cumulative pore volume; (**b**) differential pore volume

pore size will promote electrical current flow, which lowers electrical resistivity.

4.6.2 Agar-Treated Sand

The combined results of the MIP tests show that there are two different types of pores. The first is macropores, which are defined as pores with a diameter of more than 1000 nm. They are analogous to the enormous holes between sand grains that exist when Agar's pore filling is absent. The spaces between agar gel networks that cover sand particles and fill their pores make up the majority of the second type, which are known as micropores. The cumulative pore volume with pore diameter at various agar contents is shown in Fig. 9a. The curves are well-graded, smooth boundaries, just like the casein-treated sand, indicating that pore diameters are within the range that may be observed. When the agar biopolymer concentration grew from 1 to 2 to 3%, the total mercury intrusion increased from 0.1984 ml/g to 0.2119 ml/g to 0.2147 ml/g. However, with larger pore sizes, the differences in the cumulative pore volume of various agar biopolymers become insignificant. The mercury intrusion of the 3% agar-treated sand is decreased to less than 2% and 1% agar-treated sand as the pore diameter increases, while the 1% and 2% agar-treated sand converges to one another as the pore diameter increases. Figure 9b displays the differential pore volume distribution curves for the specimens with varying agar concentrations. Figure 9b demonstrates that various agar-content treated sand has two primary peaks. With an increase in agar concentration, those peaks will shift slightly to the left, which indicates that the pore size will also somewhat decrease. For example, 1% treated Agar shows a peak at 145574.212 nm and 90610.756 nm. As the amount of agar biopolymer is increased, these pore diameters are slightly reduced; for example, for 2% agar-treated sand, they are reduced to 145512.512 nm and 90562.475 nm, and for 3% agar-treated sand, they are reduced to 145481.687 nm and 90499.7 nm. It should be noted that the peak intensities of the 1% and 2% Agar treated sand converged, whereas the peak intensities of the 3% agar-treated sand are lower than 2% and 1%. This suggests that the macropore changes slightly with the agar content while the micropores remain there in the soil. The electrical resistivity of agar-treated sand is consistent with this type of pore shape the behavior of sand with varying agar content, where the electrical resistivity is little altered as the agar content is increased and exhibits convergent values for various contents. The electrical resistivity of agar-treated sand that had been dried for 21 days decreased from 418.507Ω.m to 392.617Ω.m to 391.022Ω.m as the agar content was raised from 1 to 2 to 3%. Also, as the agar concentration is raised, the cumulative pore volume of the various agar content of the treated sand increases. The electrical current flow will be improved when the pore volume increases, which will lower the electrical resistivity.



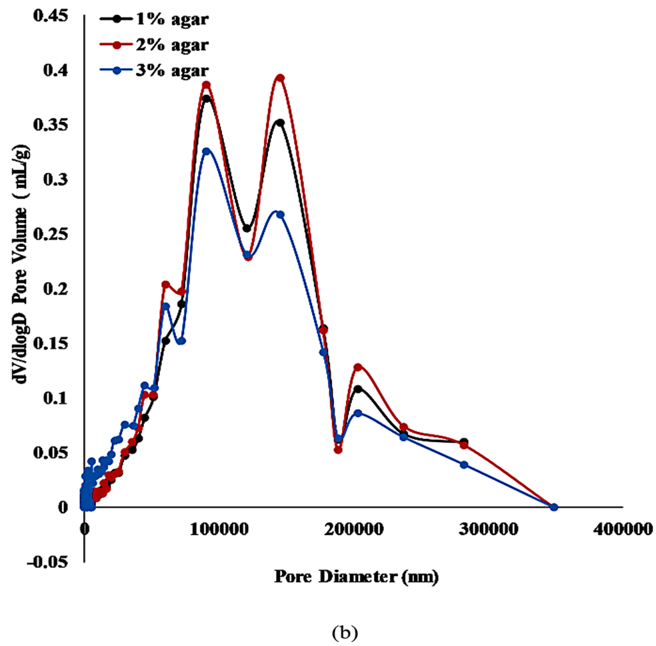


Fig. 9 Mercury intrusion porosimetry results of different agar content treated sand: (**a**) cumulative pore volume; (**b**) differential pore volume

4.7 Unconfined Compressive Strength of Biopolymer-Treated Soil

4.7.1 The Effect of Biopolymer Type and Content on the Strength

The specimens that had been dried for 21 days and prepared at various relative densities (different porosities) were subjected to an unconfined compressive test. The relationship between strength, relative density, and biopolymer content and type is shown in Fig. 10. Agar biopolymer has greater efficacy in enhancing the strength of Harbin sand in comparison to casein biopolymer. For example, the 1% agar-treated sand's unconfined compressive strength (UCS) at 85% relative density was 2061.78 KPa, while the 2% casein-treated sand's UCS at 85% relative density was 1121.19 KPa. Nevertheless, UCS increases regardless of the type of biopolymer as the biopolymer content increases. As the agar concentration grew from 1 to 3% at 85% relative density, the UCS increased from 2061.78 KPa to 4851.54 KPa. Likewise, strength increased from 1121.19 KPa to 5977.76 KPa at 85% relative density when casein concentration was increased from 2 to 4%. These findings concur with earlier research, including (Chang et al. 2015, 2018).

4.7.2 The Link between Resistivity and Strength

Because it was noted in the literature that the geotechnical characteristics of the soil that are connected with the electrical resistivity affect how its strength behaves, the correlation between electrical resistivity and UCS was investigated. UCS is a crucial factor in determining how well biopolymer-treated sand performs (USEPA 2000). The main determinants of electrical resistivity and UCS are found to be moisture content (dehydration duration), void ratios (degree of compaction), and biopolymer content and type in biopolymer-treated sand (Chang et al. 2020; Fatehi et al. 2021). In light of this, Fig. 11 illustrates a relationship between UCS and the electrical resistivity of sand treated with a biopolymer. The outcome demonstrates that the strength and electrical resistivity of casein-treated sand are linearly related and depend on the casein content with R^2 of 0.945, 0.966, and 0.999 for 4%, 3%, and 2% casein-treated sand respectively. In contrast, the strength and electrical resistivity of agar-treated sand showed a weak linear correlation, which resulted in the optimization of the relationship as a second-degree polynomial. The fit curve line between the electrical resistivity of agar-treated sand and strength is a second-degree polynomial function, which demonstrated the highest R^2 values of 0.851, 0.993, and 0.703 for 3%, 2%, and 1% agar-treated sand, respectively.

As a result, it can be said that casein biopolymer has a similar effect on soil strength and electrical resistivity across a range of porosity ratios, whereas agar biopolymer has a different effect—one that the electrical resistivity increases, the strength of Agar treated sand increases two times. As a result, Eqs. 7 and 8 show how the electrical resistivity and strength of sand treated with casein and Agar, respectively, relate to one another.

$$\mathrm{UCS} = \mathrm{A}\rho - \mathrm{B} \tag{7}$$

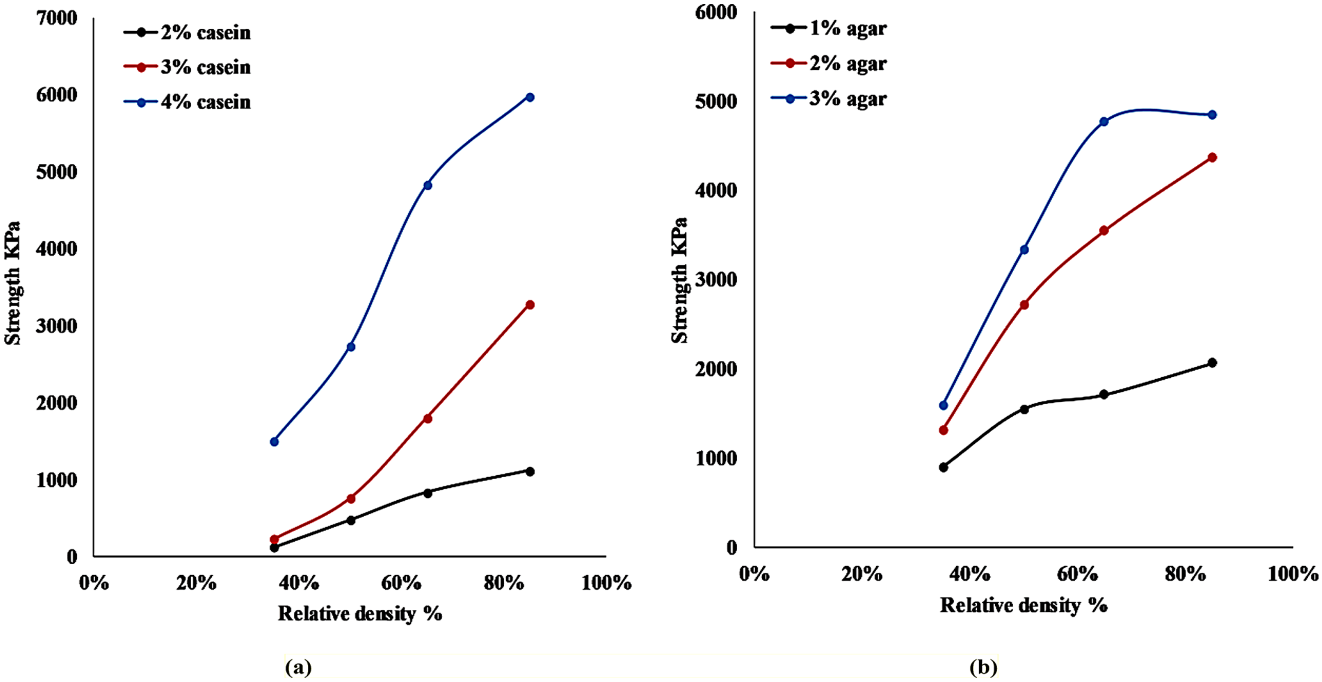


Fig. 10 The effect of biopolymer content and relative density on the strength of (**a**) casein-treated sand; and (**b**) agar-treated sand

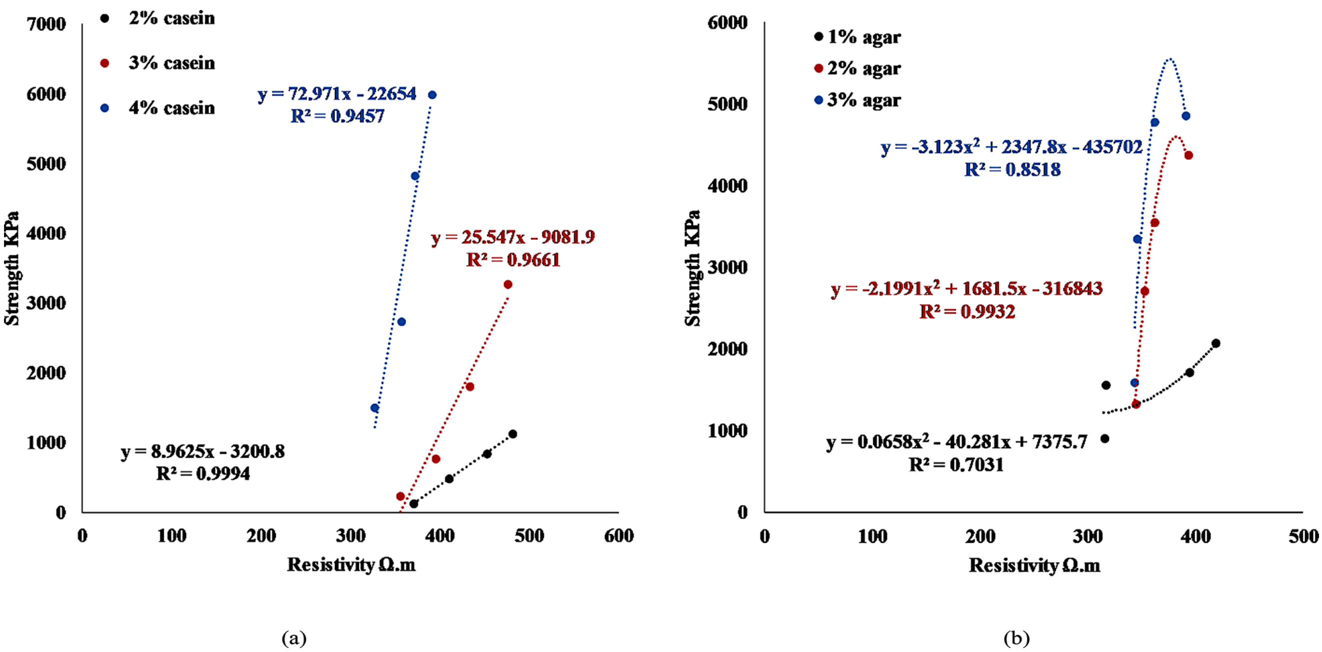


Fig. 11 Relationship between unconfined compressive strength and electrical resistivity: (**a**) casein-treated sand ; (**b**) agar-treated sand

$$\mathrm{UCS} = \mathrm{A}\rho^2 + \mathrm{B}\rho + \mathrm{c} \tag{8}$$

UCS is the unconfined compressive strength, ρ is the electrical resistivity, and A, B, and c values depend on the biopolymer content and type. Table 3 presents the values of A, B, and c parameters dependent on the type and content of biopolymers. These values are derived using the linear function and second polynomial function shown in Fig. 11. For casein-treated sand and Agar treated sand, the minimal R^2 found is 0.94 and 0.704, respectively. Electrical resistivity as a cost- and time-efficient approach can be utilized to measure the mechanical behavior of stabilized soil, as was discovered in both our study and earlier studies. According to Vincent et al. (2017).'s examination into the electrical resistivity of newly made uncured and cured soil-cement materials, resistivity in soil-cement mixture rises along with

Table 3 The values of A, B, and c parameters of Eqs. 7 and 8 are dependent on the type and content of biopolymers

Biopolymer type	Biopolymer content	A	B	c	R^2
Casein	2%	8.962	3200.8		0.9994
	3%	25.547	9081.9		0.9661
	4%	72.971	22654.0		0.9457
Agar	1%	0.0658	40.281	7375.7	0.7031
	2%	-2.199	1681.5	-316,843	0.9932
	3%	-3.123	2347.8	-435,702	0.8518

cement quantity and curing time in a manner comparable to how unconfined compressive strength rises.

There is a significant correlation between resistivity and unconfined compressive strength, according to Liu et al. (2008)'s examination of the resistivity fluctuation of soils treated with cement. A linear relationship between cement paste resistivity after 24 h and 28-day compressive strength was demonstrated by Wei et al. (2012). It was straightforward to predict the cement paste's compressive strength at 28 days utilizing a quantitative relationship made with the cement paste's resistivity after 24 h. In our work, the electrical resistivity is related to the unconfined compressive strength of casein-treated sand linearly and to the unconfined compressive strength of agar-treated sand by a second-degree polynomial. Consequently, electrical resistivity, which is easily measured in the field, can be used to estimate the strength capabilities of biopolymer-treated sand. Engineers can select an appropriate amount of biopolymer and compaction level to fulfill the real project's strength requirements by combining the resistivity formula produced in this study.

4.8 Artificial Neural Network

From Archie's law to the most recent model, various models have been used in the literature to predict the electrical resistivity of soil. For instance, Fukue et al. (1999) developed a structural model with three-phase components—solid, liquid, and gas—made up of serial and parallel portions, each of which has a different electrical conductivity, and provides details on soil structures. Melo et al. (2021) evaluated the power, exponential, and logarithmic models by researching the impact of compaction on the connection between electrical resistivity and soil water content in Oxisol. In order to predict the electrical resistivity of cement-stabilized lead-contaminated soils, Cao et al. (2018) developed a model using unique parameters known as the "porosity-lead content/cement content-curing time ratio." To the author's knowledge, a few studies have been done on predicting electrical resistivity using artificial intelligence techniques like artificial neural networks. Furthermore, it is unclear how significant every factor is in determining electrical resistivity. To predict electrical resistivity and quantify the relative important of the factors that effect it, predictive methods like artificial neural networks may be helpful. As a result, an artificial neural network was built using the test data.

The main factors influencing soil resistivity are water content, porosity, density, degree of saturation, particle shape, orientation, and ion concentration of pore solution (Kibria and Hossain 2012; Oh et al. 2014). In addition to the aforementioned factors, the kind, quantity, and curing period of the binder have an impact on the electrical resistivity of stabilized soil. Our study used six different parameters (biopolymer type (BT), biopolymer content (BC), dehydration time (T), porosity (P), the synthesis parameter of (porosity/(biopolymer content* dehydration time)(POT), and water content(WC)) as the input of an artificial neural network and electrical resistivity as the output to estimate the electrical resistivity of biopolymer-treated sand. In addition to being more cost-effective during operation, determining the relative importance of factors that affect electrical resistivity could therefore help in establishing the right implementation conditions for the quality control of subgrade/subbase treated by biopolymer. By minimizing the difference between the target and experimental outputs, the predictive model is built using the experimental data set to determine the factors' relative significance. A number of methods, such as the connection weights approach, Garson's algorithm, partial derivatives, forward stepwise addition, backward stepwise removal, and others, can be used to evaluate the importance of the input variables for the ANN model (Olden et al. 2004). For this study, Garson's algorithm technique and connection weight approach were chosen since they are straightforward and extensively utilized by academics(Leong et al. 2018; Rezazadeh Eidgahee et al. 2020). This study built the ANN model using the MATLAB R2021a neural network toolkit. A linear function was used, and backpropagation was used as the training method. The effectiveness of the ANN model was assessed using measures of mean square error (MSE) and R^2. 70% of the data were used for training, 15% for testing, and 15% for validation.

In order to forecast the electrical resistivity, many hidden layers with various neurons were looked. However, a hidden layer with 41 neurons helped achieve the highest R^2, which was 0.798. Figure 12a depicts the regression line between the experimentally tested data and the predicted tested data obtained from the ANN model. The coefficient of determination ($R^2 = 0.798$) demonstrated the model's strong agreement with the data. Figure 12b's regression plot displays the entire experimental data as well as the global forecasted data generated by the ANN model. The coefficient of determination ($R^2 = 0.786$) demonstrated the

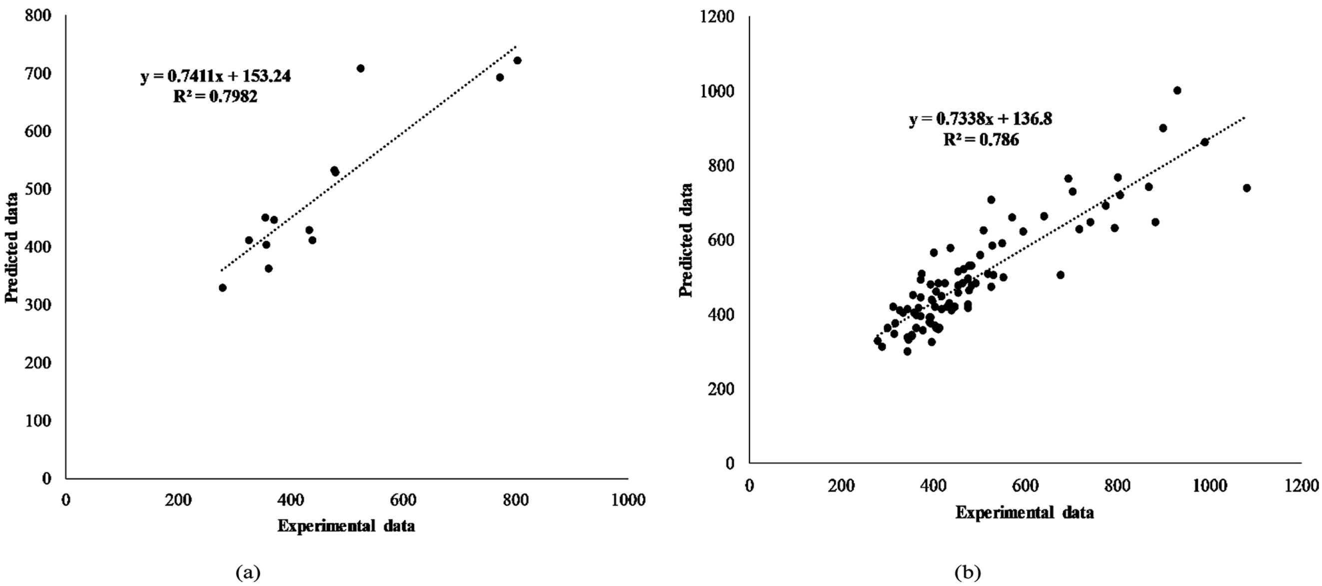


Fig. 12 The regression curve between the experimental data and the predicted data derived from the ANN model **a**) tested data; **b**) global data

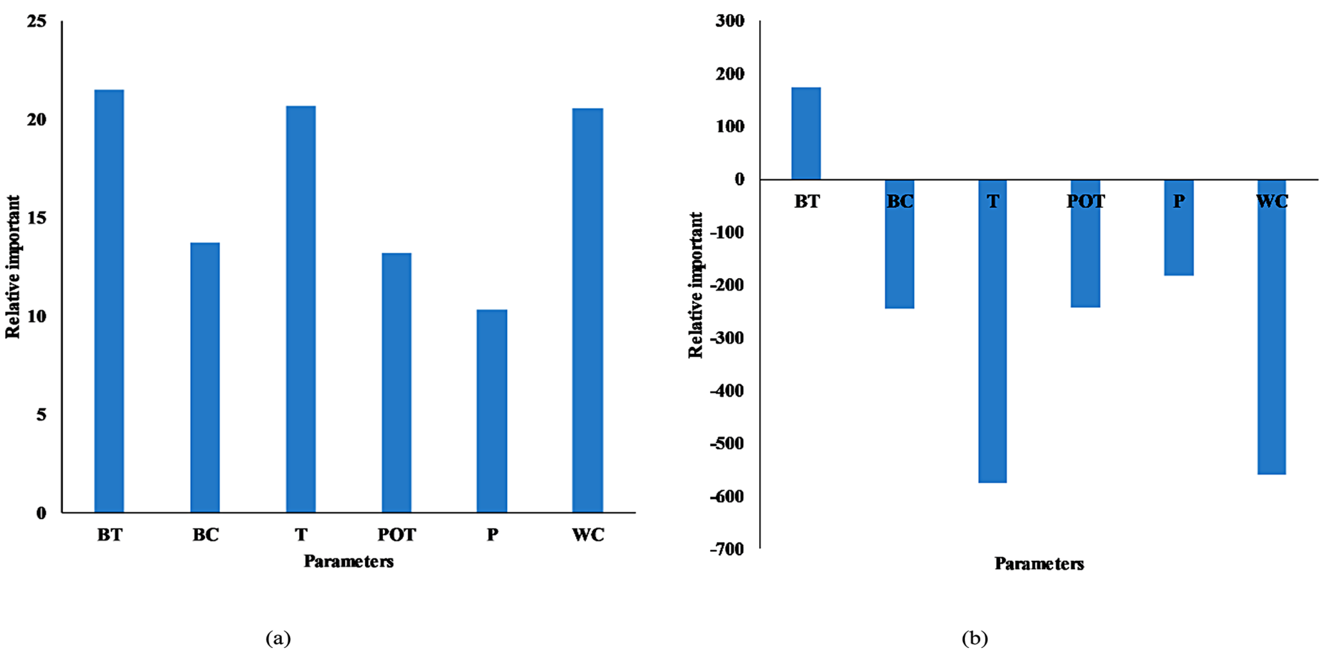


Fig. 13 The relative importance of the variables is based on **a**) Garson's algorithm; **b**) connection weight

model's strong agreement with the data. In Garson's algorithm, the contribution's absolute value was examined to determine the input variables' relative significance. There was no directionality in the interactions between the input and output variables since nonnegative values were present as a result of the use of absolute values. Figure 13a shows the relative weights of the input variables according to Garson's algorithm. The following is the ranking of the significance of the input variables: Biopolymer type > dehydration time > water content > biopolymer content > porosity/(biopolymer content * dehydration time) > porosity.

The biopolymer type, dehydration duration, and water content contributed nearly identical proportions, showing that both factors significantly impact the outcome. Because casein biopolymer is an anionic biopolymer and agar biopolymer is a neutral biopolymer (Fatehi et al. 2021), the type of biopolymer is expected to have a substantial impact on the electrical resistivity of biopolymer-treated sand. The concentration of ions in the pore solution tends upward after the addition of calcium caseinate, and the presence of ions improves the flow of electrical current. As a result, the solution's electrical resistance reduces as the casein

concentration does. However, there are different ways to explain how agar biopolymers work. In the agar gels, water molecules congregate in the crevices between the Agar double helices, increasing the stability of the double helix. Agar molecules normally form double helices with a threefold screw axis. If agar concentrations are increased, the density of double helices increases, resulting in more three-dimensional gel networking decreasing the maximum dry density. Hence, the electrical resistivity of soil treated with Agar will decrease when agar concentrations are raised because of the highest gaps. The SEM image and MIP test further demonstrate that the casein biopolymer's geometry and dispersion inside the sand differ from the agar biopolymer's. Thus, the type of biopolymer is expected to influence electrical resistivity.

The literature has demonstrated how the length of the dehydration time affects the geotechnical characteristics of the biopolymer-treated soil, causing a decrease in moisture content and an increase in unconfined compressive strength (Chang et al. 2016; Fatehi et al. 2021). The volumetric shrinkage in biopolymer-treated soils during the air drying process causes the hydrogel to transform into three-dimensional biopolymer gel networking, increasing the gaps inside the soil. This has a significant impact on the electrical resistivity of the biopolymer-treated sand. A great deal of research has shown how water content affects electrical resistivity. For example, in a study examining the viability of the resistivity method for the investigation of the spatial and temporal variations in soil moisture in the Vallaccia catchment, Calamita et al. (2012) demonstrated a strong correlation between electrical resistivity and soil moisture. Similarly, Alamry et al. (2017) study on the spatial and temporal monitoring of soil moisture using surface electrical resistivity tomography in Mediterranean soils revealed a strong correlation between moisture content and electrical resistivity. It can be demonstrated that the second rank of parameters affecting the electrical resistivity of sand treated with biopolymers is the biopolymer content and porosity/(biopolymer content*dehydration time).

Our study's MIP test revealed that when the biopolymer content rose, the pore size of the biopolymer-treated sand rose as well, causing the resistivity to fall. Our study showed a similar learning to the electrical resistivity of the cement-treated soil, which was significantly influenced by the cement amount and curing duration (Zhang et al. 2014). However, the electrical resistivity of biopolymer-treated sand was negatively impacted by the biopolymer content and dehydration duration, in contrast to the cement-treated soil. Beginning with Archie's law, which links the electrical resistivity of saturated sand (ρ) to the electrical resistivity of pore fluid (f) and porosity(n) to more contemporary studies, the impact of porosity on the electrical resistivity of soil has been demonstrated in earlier research. For instance, Cardoso (2016) studied how the electrical resistivity of sand that had been artificially cemented was impacted by the porosity and tortuosity of the material.

The connection weights approach was also utilized to evaluate the significance of each input variable to the output in addition to Garson's algorithm. The connection weights approach, like Garson's algorithm, justified the significance of each input variable to the output by multiplying the connection weights between input and hidden neurons and between hidden and output neurons. However, this method did not assess the absolute value of each contribution. The sum of each contribution made by the input, hidden, and output neurons was used to rate the significance of each input variable. The outcome's ranking was based on the summation product, so the evaluation depended on whether the result was positive or negative. The relevance of the inverse link between these input variables and the output is demonstrated by a negative number, which signifies a negative impact on the output. It should be noted from Fig. 13b that all parameters, with the exception of biopolymer type, have a negative impact on electrical resistivity. Water content has the most significant negative impact. The connection weight method's evaluation of each factor's contribution that has an adverse impact revealed a similar ranking to Garson's algorithm. The dehydration time and water content had the greatest detrimental effects, which were subsequently followed by the biopolymer content, (porosity/(biopolymer content * dehydration time)) and porosity. If we take into account the directionality of the interactions between the input and output variables, it is clear that the kind of biopolymer does not have a negative influence.

5 Conclusion

This study has investigated and discussed in detail the electrical resistivity of two types of biopolymer treated sand including Casien tread sand and agar treated sand. Various factors, such as dehydration time, porosity, initial water content, and relative density were examined as a function of the electrical resistivity for the two types of biopolymer treated sand. In which, the electrical resistivity for the two types of biopolymer treated sand is inversely correlated with the biopolymer content and dehydration time. Electrical resistivity increased with decreasing porosity and initial water content. For casein treated sand, the obtained data from MIP tests indicated that the pore size increases by increasing the amount of casein content. Furthermore, the electrical resistivity of the casein treated sand has a direct relationship with its unconfined compressive strength. On the other hand, the results declared that the cumulative pore

volume of agar treated sand increases with the increase of agar concentration in the sand, resulting in an increase in the electric current flow which reduces its electrical resistivity accordingly. Moreover, the relation between the electrical resistivity of the agar treated sand and its unconfined compressive strengths is well described by the second-degree polynomial relationship. Artificial natural network as a predictive model, was employed to predict the electrical resistivity, and determine the relative significant influence of different factors affecting the electrical resistivity of the two types of biopolymer treated sand.

Author Contributions Mohammed F. Y. Ashour wrote the main manuscript text and prepared figures. All authors reviewed the manuscript."

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

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